NEWBORN CRY PITCH PREDICTING REACTION TIMES AND ATTENTION DISENGAGEMENT IN 8-MONTH-OLD INFANTS

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ABSTRACT

Newborn cry acoustics are thought to reflect the integrity of the central nervous system as well as the sensitivity of the peripheral nervous system. In previous studies, features of newborn cry pitch such as high fundamental frequency (f_0), and high variability (*SD*) of the f_0 have been noted as risk markers for later cognitive outcomes among infants having varying birth risk factors. It is unknown if this applies to healthy full-term infants. As a part of a larger study, this study investigated the relation of these two newborn cry frequency characteristics and information processing in 8-month-old full-term, full birth weight infants. Saccadic reaction times to peripheral target stimuli and the probability to disengage attention from different facial expressions (neutral, happy, fearful) and non-face stimuli were measured with corneal-reflection eye-tracking.

Based on the longitudinal data collected from 44 infants, average cry frequency had a significant negative relation with mean attention disengagement probability. Infants with higher frequency cry as newborns were less likely to disengage their attention at 8 months. The strength of the relation was the same when information on birth weight, birth head circumference, and chronological age at the follow-up was controlled for. The variability of the cry frequency was not related to attention disengagement. Based on longitudinal results (n = 54) of the saccadic reaction time data, there was no significant relation nor predictive value of cry frequency variables to infant saccadic reaction times at 8 months.

In summary, a significant long-term association emerged between average cry frequency and attention disengagement probability, indicating that mean cry frequency, but not the high variability of the cry frequency, might be indicative of neural organization and later development of visual attention in full term newborns beyond newborn body size and age. The results of this study should be verified with low-risk non-clinical populations, and more focus should also be directed to potential modifiers of the relation such as socioemotional risk factors at birth and in the first year of life.

KEYWORDS: newborn, infant, cry pitch, attention disengagement, saccadic reaction time, social cognition, eye tracking

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TIIVISTELMÄ

Vastasyntyneen itkun akustiikan on arveltu heijastavan keskus- ja ääreishermoston kehitystasoa. Aiemmissa tutkimuksissa vastasyntyneiden itkun akustisten ominaisuuksien kuten keskimääräisesti korkean perustaajuuden (f_0), ja perustaajuuden suuren vaihtelevuuden ($SD\ f_0$) on havaittu ennustavan heikompaa kognitiivista kehitystä vauvoilla, joilla on merkittäviä lääketieteellisiä riskitekijöitä syntyessään. Ei vielä tiedetä, ennustaako varhainen itku kognitiivista kehitystä myös terveillä täysiaikaisesti syntyneillä vauvoilla. Osana laajempaa tutkimusprojektia, tässä tutkimuksessa tutkittiin yhteyttä vastasyntyneiden itkun perustaajuuden (f_0) ominaisuuksien (korkeuden ja vaihtelevuuden) ja myöhemmän tiedonkäsittelyn välillä terveillä täysiaikaisilla vauvoilla. Seurantakäynnillä 8 kuukauden iässä silmänliikkeistä mitattavia reaktioaikoja ja tarkkaavuuden irrottamista eri kasvonilmeistä (neutraali, iloinen, pelokas) ja kontrolliärsykkeestä mitattiin silmänliikekameraa hyödyntäen.

Tässä pitkittäistutkimuksessa (n = 44) havaittiin, että itkun perustaajuuden korkeus (f_0) oli negatiivisesti yhteydessä tarkkaavuuden irrottamisen todennäköisyyteen 8 kuukauden iässä. Vauvat, joilla oli keskimäärin korkeampi itkun perustaajuus vastasyntyneenä, irrottivat vähemmän todennäköisesti tarkkaavuuttaan huomion kohteena olevasta ärsykkeestä 8 kuukauden iässä. Yhteyden voimakkuus pysyi samana, kun lapsen ikä, syntymäpaino ja pään ympärysmitta syntymähetkellä ja itkun vaihtelevuus oli otettu huomioon. Itkutaajuuden vaihtelevuus ($SD\ f_0$) ei ollut yhteydessä tarkkaavuuden irrottamistodennäköisyyteen. Tässä pitkittäistutkimuksessa ei havaittu kummankaan vauvan itkun perustaajuusmuuttujan osalta merkitsevää yhteyttä silmänliikkeiden reaktioaikoihin 8 kuukauden iässä (n = 54), eikä molempien itkun taajuusmuuttujien yhteinen selitysosuus usean muuttujan lineaarisessa regressiomallissa ollut merkitsevä reaktioaikojen suhteen, kun lapsen ikä, syntymäpaino ja -pään ympärysmitta oli huomioitu.

Yhteenvetona, tässä pitkittäistutkimuksessa havaittiin yhteys vastasyntyneen itkun korkean perustaajuuden ja tarkkaavuuden irrottamistodennäköisyyden välillä 8 kuukauden iässä. Tämä yhteys viittaa siihen, että korkea taajuus on yhteydessä keskushermoston organisaatioon ja ääreishermoston herkkyyteen ja tätä kautta vaikutus heijastuu myös tarkkaavuuden prosesseihin. Jatkossa tästä aiheesta on tärkeää tehdä tarkentavaa tutkimusta vauvoilla, jotka ovat syntyneet ilman, että heillä on merkittäviä lääketieteellisiä riskitekijöitä. Jatkotutkimuksissa, joissa itkun ennustevaikutuksia tarkastellaan tarkkaavuuteen liittyen, tulisi kiinnittää myös huomiota sosioemotionaalisiin riskitekijöihin syntymän ja ensimmäisen elinvuoden aikana, koska näillä tekijöillä on aiemmissa tutkimuksissa havaittu vaikutus ääreishermoston herkkyyteen ja tarkkaavuuden prosesseihin.

ASIASANAT: vastasyntynyt, vauva, itkun äänenkorkeus, tarkkaavuuden irrottaminen, reaktioaika, silmänliikkeet

PREFACE

This Master's Thesis study was part of a larger longitudinal cry study conducted in Tampere. I would like to acknowledge the large contribution of the whole Tampere cry team has made to the thesis, and give acknowledgement in regards to the contribution of cry researcher Jaana Kivinummi in guidance of cry theory and the study of cries as well as her time given to data collection, Gaurav Naithani and Tuomas Virtanen in processing the cry data, Outi Tammela in consultation of infant health related factors and Mikko Peltola and Jukka Leppänen with summarizing the eye-tracking data and consultation on infant attention related factors. I would also like to thank the valuable time given by the participants and their families.

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Tampere, 19 April 2016,

Enni Kurkela

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1 INTRODUCTION

Newborn cry is a phenomenon in which the infant produces expiratory vocalisations relating to an external or internal stimulus causing distress. Crying is believed to reflect newborn infants' neurological status, which in turn is known to predict cognitive function later in life. This connection has been observed in few previous longitudinal studies, as abnormal neonatal cry characteristics have been linked to developmental difficulties (e.g., LaGasse, Neal, & Lester, 2005; Lester, 1987). Of the many cry characteristics studied, the pitch of the cry, measured as fundamental frequency (f_0), has been the most valued and prevalent measurement of cry acoustics in infant studies (Gustafson & Green, 1989). Since longitudinal studies published on this subject matter are scarce, further investigation is warranted on the predictive qualities of newborn cry to early developing information processing abilities. This study investigated the predictive value of the cry of a newborn (measured as mean f_0 and standard deviation of f_0) to later social-cognitive outcomes at 8 months. Social-cognitive outcomes were measured as two visuospatial processes: orienting speed (i.e., saccadic reaction time or SRT) and the ability to disengage attention from different face and non-face stimuli, using eye-tracking methods. These processes of visual attention, orienting speed and attention disengagement, may hold a predictive value into the development of higher cognitive functions, self-regulation and executive functions later on in childhood (Dougherty & Haith, 1997; Rose, Feldman, & Jankowski, 2003; 2011).

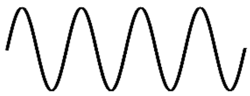
1.1 Neurophysiological models of newborn crying

Many muscle groups, cranial nerves, and brain regions participate in coordination to produce the piercing and intensive sound that is heard as crying. Typically developing infants cry by tensing up their whole bodies, and the tension of the muscles contributes to the acoustic features of the cry both in the larynx and the respiratory muscles that control breathing. Sufficient air flow through the vocal folds is required in the expiratory (i.e., breathing out) portion of the cry and this is controlled by pressure from the respiratory muscles. As enough air pressure is applied on the properly positioned vocal folds, they begin to vibrate and produce sound waves. When the air pushes forcibly through the stretched and tensed vocal folds, the tensing of the vocal folds increases the frequency of the vocal fold vibration that is heard as pitch (Laukkanen & Leino, 1999).

Fundamental frequency (f_0) is perceived subjectively as cry pitch (LaGasse et al., 2005). In cry research, the f_0 values are considered valid and critical measurements of the acoustic quality of the cry (Gustafson & Green, 1989; Michelsson & Michelsson, 1999). Table 1 summarizes the key concepts (i.e., mean f_0 and the variability of the f_0) briefly. Average newborn cry has an average fundamental frequency of approximately 440 Hz (i.e., vocal fold vibrations per second) (e.g., Rothgänger, 2003). When a painful stimulus initiates the cry, the average frequency is initially higher, nearly 500 Hz (Michelsson, Eklund, Leppänen, & Lyytinen, 2002; Rothgänger, 2003). This difference may be due to the varying states of distress and arousal, as some cries indicate slowly escalating discomfort while other cries begin abruptly and intensely due to pain-inducing conditions. Despite these differences, many concur that the normative values for mean cry f_0 are between 400 and 600 Hz in newborns (for reviews, see Michelsson, Todd de Barra, & Michelsson, 2007; Zeskind, 2013). The variability of the f_0, on the other hand, indicates how much change there is in the frequency across multiple expiratory cries. In full-term newborns, the cry frequency changes relatively little in pain cry (mean $SD = 95$ Hz; Michelsson et al., 2002) and hunger cry ($SD = 49$ Hz; Rothgänger, 2003), since the neural structures controlling the larynx are well-organized and have stable control over the vocal folds (LaGasse et al., 2005; Zeskind, 2013). Regarding the f_0 variability, momentary and short shifts in cry to 1000-2000 Hz are considered somewhat atypical (Zeskind, 2013). This type of hyperphonation is only occasionally observed in healthy newborns.

Table 1

Concept summary of f_0 characteristics in cry

Cry quality characteristic	Perceived as	Examples of phenomena	Illustrated examples of f_0 sound waves
Mean fundamental frequency (f_0)	Average cry pitch across one expiratory phase, or the average of multiple phases	A. High pitched cry or shriek, hyperphonation B. Low pitched cry	 
Variability of fundamental frequency (f_0)	Cry pitch change across one expiratory phase, or the average change across multiple phases	C. Highly changing cry pitch D. Monotone cry pitch	 

In the peripheral nervous system, the cry f_0 characteristics are determined by vagal and parasympathetic nervous system control. Although some models theorize that crying requires a more holistic input from the 9-12th cranial nerves, there is consensus in the literature that the biological mechanism behind the f_0 is the vagal input to the larynx (for review, see Green, Irwin & Gustafson, 2000). The vagus (i.e., the 10th cranial nerve) is a complex nerve that regulates the actions of the vocal folds, respiratory muscles, and the heart in addition to the digestive system (Sherwood, 2007). Thus, it is one of the most important sections of the parasympathetic nervous system and critical in, for example, emotion regulation (Sherwood, 2007). Research suggests that the active functioning of the inhibitory parasympathetic nervous system and the vagus nerve is required to produce typical cry acoustics (Lester, 2015). When these systems are functioning less actively, this is naturally observed as more high-pitched and more variable f_0 in cries (e.g., Lester, 1976). Altogether, fundamental frequency of cry seems to be very well influenced by the neural structures controlling the parasympathetic nervous system and the vagus nerve.

In the central nervous system, the cranial nerves originate from the lower brainstem. Fundamentally, the brainstem is believed to create most of the variations in the f_0 cry acoustics (Zeskind, 2013), and most neural models highlight the brainstem as having the largest influence in cry acoustics since it regulates rudimentary motor functions, respiratory functions and vagal input (Geva & Feldman, 2008; Newman, 2007). Based on mammalian studies, crying behaviour is initiated through arousal of the limbic-hypothalamic system and then produced in coordination with neural areas within the brainstem (LaGasse et al., 2005; Newman, 2007). The amygdala and the hippocampal areas may be central in the initiation of different types of crying, while networks in the midbrain regions most likely regulate the pattern in which the cry is produced (Lester & Boukydis, 1992; Newman, 2007). Later developing cortical brain areas are needed, however, to spontaneously initiate the cry and to create more complex and voluntary cry patterns. Since during the first weeks of life the brain functions from within its core processes, newborns have very little, if any, neurophysiological control over their cry-utterances (e.g., Zeskind, 2013). Studying the cry acoustics in the neonatal stage may have the distinctive advantage that the crying is reflexive and learned cry behaviour has not yet emerged. Newborn cry acoustics can therefore reflect the stability and functioning of the central nervous system without the influence of higher cognitive processes (Michelsson & Michelsson, 1999).

1.2 Newborn cry characteristics in relation to the neurological status of infants

The strong connection between the central nervous system (CNS) integrity and neonatal cry characteristics has been well documented. In almost all cases, damage or malformation in the CNS increases the neonatal cry frequency relative to healthy and typically developing infants (LaGasse et al., 2005). Abnormal cry acoustics and increased f_0 values have been found in newborns with a myriad of prenatal or perinatal conditions affecting the CNS such as: head trauma, hydrocephalus, asphyxia and limitation of the blood flow, malnourishment as well as prenatal exposure to toxins (e.g., tobacco or drugs) damaging the nervous system in utero (LaGasse et al., 2005: Lester, 1976; Lester et al., 2002; Nugent, Lester, Greene, Wieczorek-Deering, & O'Mahony, 1996; Michelsson & Michelsson, 1999; Quick, Robb, & Woodward, 2009). When the structures that control the function of the larynx, mainly the brainstem but also higher cortical areas, are affected by an insult, it is reasonable that the repercussions can be heard in the sound of the cry. However, it has also been speculated that smaller deviations from the mean cry characteristics may represent more normative individual differences in CNS organization among otherwise healthy newborn babies (Zeskind, 2013).

Research further indicates that the brain's immaturity and undeveloped organisation may furthermore constitute to the cry pitch, since much brain development occurs in the last trimester of pregnancy (DiPietro, 2008). For example, prematurely born neonates (born less than 37 weeks of pregnancy) cry at an atypically high cry pitch both at birth and when aged to the expected date of delivery (Lester, 1987; Michelsson et al., 2007). The more immature the preterm infant is, the higher the mean cry pitch typically reaches (Michelsson et al., 2007). While the small body size of the infant is also known to contribute to a higher pitch of the cry (Branco, Fekete, Rugolo, & Rehder, 2007), the effect has often been small and observed in differences in the minimum f_0 values, not the average f_0 values (Rautava et al., 2007; Wermke & Robb, 2010). Therefore, in preterm infants, more high-pitched cry cannot be explained by the small size of the infant alone. Geva and colleagues (2013) studied the development of preterm infants and concluded that the brainstem, which is also highly relevant in production of cry acoustics, is particularly susceptible to functional and organizational changes. Moreover, they found that abnormal function of the brainstem in preterm infants may be connected to later attentional regulation deficits, low executive control and social information processing impairments (Geva & Feldman, 2008; Geva et al., 2014). It is important to extend these previous findings and study the neurobehavioral organization in full-term (i.e. 37-42 weeks) and full birth weight infants (i.e., over 2500 grams), and determine whether variation in cry f_0 can predict later social cognitive development (see also Zeskind, 2013).

1.3 Cry f_0 acoustics predicting broad developmental outcomes in infants

Although high-pitched cry has been documented in infants who are generally at risk for poor cognitive development, the direct long-term relationship between cry and cognition has received relatively little attention. At least two risk groups have, however, been studied in this regard. First, in a preliminary study by Lester (1987), the cries of 13 healthy full-term newborns and 18 preterm infants were recorded soon after birth. Among other newborn cry characteristics, the mean f_0 and the variability of the f_0 were extracted from 10 seconds of crying. The developmental status of the same infants was then assessed at 18 months of age. The study discovered that out of the many cry features the mean f_0 and the variability in the f_0 were the ones that had long-term associations with the Mental Development Index (MDI; in Bayley Scales of Infant Development -I). The MDI measured holistically many aspects of cognitive development (e.g. memory, visual-motor, problem solving, social) and language development (see, Lennon, Gardner, Karmel, & Flory, 2009b, for review). In Lester's (1987) study, the higher the fundamental frequency (f_0) was, the lower the MDI scores subsequently were at 18 months. Also, the more variable the newborn cry f_0's were, the lower the MDI scores were. The variability in the f_0 in neonatal cry was still related to cognitive development even up to 5 years of age, as high variability of the f_0 was associated with low cognitive scores, low verbal scores, and low perceptual scores in the McCarthy General Cognitive Index.

Second, very similar findings to Lester (1987) were observed in a study that examined the cries of 8 neonates who had been exposed to methadone and various drugs during pregnancy, and their 12 non-exposed controls who came from low socioeconomic backgrounds (Huntington, Hans & Zeskind, 1990). Both groups had a high incidence of pre- and perinatal complications, and the cry f_0 characteristics did not differ between the groups when recorded in the first days after birth. Regardless, the newborn cry f_0 from a single cry expiration was associated with later cognitive development. Similarly to Lester (1987), the mean f_0 correlated negatively with MDI scores at 4 and 8 months of age (Huntington et al., 1990). Higher variability of f_0 was likewise related to low MDI scores at 8 months, 12 months, and at 18 months. As the infants aged, the strength of the relationship between the variability of f_0 and mental developmental indexes faded and the factors correlated only marginally at 24 months. This may be because environmental effects on cognition become more prominent after the first year of life (Lennon et al., 2009b). Hence, it may be more informational to study the connection between cry and information processing abilities during the first year of life.

While it was noted in the two studies that birth risk factors such as prematurity and exposure to drugs did not by themselves predict later cognitive development, this notion has been questioned (e.g.

Green et al., 2000). Huntington and colleagues (1990) instead proposed that the cry f_0 values were the markers that best differentiated the infants who recovered from their early life adversities to typically functioning infants from those who suffered cognitive deficits later on in childhood. The neonatal cry f_0 would seem to be a moderately strong marker for risk for poorer developmental outcomes in infants who have certain birth risk factors. The predictive value of cry f_0 may be strongest among infants in risk-groups, and hence it is important to examine long-term associations of newborn cry to risks of attention-related problems and issues with executive function, learning difficulties, and delayed cognitive development. However, at the same time the cause of the connection cannot be investigated without a certain amount of bias, if infants have medical and neurological issues. Although the two preliminary findings (Huntington et al., 1990; Lester, 1987) were congruent, a serious gap in this field of research is the lack of investigation in full-term, full-weight infants regarding newborn cry f_0 values as indicators of future cognitive capabilities (Zeskind, 2013). In addition to studying more normative populations, also larger sample sizes should be pursued than those used in prior studies.

1.4 Cry f_0 acoustics predicting specific information processing abilities

A conceptual model by Geva and Feldman (2008) highlights that the cognitive processes that reflect the functioning of the brainstem and the limbic system best are self-regulation, behavioural inhibition and social cognitive information processing. It might be more pertinent for future studies to focus on some of these factors as outcome measures when considering the previously described neurophysiological models of crying. Thus, rather than using broad and comprehensive outcome measures of infant development (e.g. MDI), the relationship between neonatal crying and later information processing abilities may be explored by measures that capture more specific aspects of cognition. This may allow the cognitive methods to be sensitive to normative variation, instead of simply differentiating between typical and atypical development (Rose et al., 2003).

While the cries of younger babies are considered to be more reliable in terms of representing neural organization (Zeskind, 2013), the younger age of infants can create a true challenge for accurately and objectively measuring cognition (for review, see Lennon, Gardner, Karmel, & Flory, 2009a). The approach of exploring a single aspect of cognition may thus be useful, and yet still have predictive validity over cognitive development in childhood. For example, when measured in infancy, many visual attention processes have been found to predict cognitive functions, executive functions, and intelligence later in childhood (Cuevas & Bell, 2014; Fagan, Holland, & Wheeler, 2007; McCall & Carriger, 1993; Rose & Feldman, 1995). Attention and processing speed are considered elementary components of cognition in infancy (Rose, Feldman, Jankowski, & Van Rossem, 2005; 2008). Both are thought to influence more complex cognitive functions and eventually through these higher cognitive functions become the "building blocks" of general intelligence (Rose et al., 2005; 2008).

Processing speed. During infant development, the growing brain myelinisation generally contributes to faster speed of information processing (Luna, Velanova, & Geier, 2008). Infants' spontaneous gaze (consisting of fixations and rapid saccadic eye movements) can be used to study infant reaction times in oculomotor tasks. Saccadic reaction time (SRT) measures the time it takes for the infant to notice the sudden shift of an object to another location, choose to pursue it, and initiate precise motor responses of the head and eyes to that target (Canfield, 1995). This ability of pursuing a target with corresponding head- and eye-movements appears to be adult-like as early as 6 months after birth (Luna et al., 2008). Oculomotor tasks, like those that employ the SRT, have been used as indicators for neurocognitive status in a multitude of studies (see reviews from Luna et al., 2008; Sweeney, Takarae, Macmillan, Luna, & Minshew, 2004). For example, faster reaction times may be indicative of less developmental risk factors such as medical risks (Rose, Feldman, & Jankowski, 2002), while on the other hand, delayed and long SRTs can indicate deficits in functional and structural neural organization that might influence overall executive control and intelligence (e.g., Dougherty & Haith, 1997; Haishi, Okuzumi, & Kokubun, 2011; Rose et al., 2011). Reaction time tasks in infancy have been found to have good predictive validity to later cognitive and intellectual development prior to school age, in which longer reaction and looking times indicate poorer outcomes on intelligence and executive function (Dougherty & Haith, 1997; Cuevas & Bell, 2014).

Faster speed of processing in the first year of life often corresponds with more mature patterns in attention and executive function (e.g. Rose et al., 2002). Infants with faster processing speed, who need less time to look at objects, are more likely divide their attention more broadly and shift attention more frequently (Jankowski & Rose, 1997). Short lookers are also more prepared to disengage their attention (Frick, Colombo, & Saxon, 1999). The brainstem has ascending connections to higher brain areas (e.g., the midbrain that contains oculomotor nerves for controlling eye movements) through the reticular activation system (RAS) that is relevant in directing attention (Sherwood, 2007). The RAS also regulates vigilance, behavioural arousal and orienting to novel stimuli and distractors, and contributes to habituation to repeated stimuli by filtering out sensory information **(**Semrud-Clikeman & Teeter Ellison, 2009**).** While the relationship between cry acoustics and visual attention orienting has remained unstudied, one auditory attention study implied that atypical cry f_0 might be a marker for risk for attention deficits with infants who have insults to the central nervous system in the first year of life (Lester, 1976).

In Lester's (1976) study, higher mean f_0 cries were related to a smaller cardiac orienting response to a novel sound stimulus at 12 months in both malnourished and well-nourished infants. A normal orienting response (heart rate deceleration to novel sound stimuli) was found in infants who cried with typical cry characteristics. Lester (1976; 2015) postulates that high cry f_0 may be linked to attentional deficits and low-level orienting through central nervous system function. However, the predictive value of cry f_0 as a marker for risk cannot be established from concurrent measurements, as these findings merely provide support to the neurophysiological connection between crying and one type of attention orienting. This connection, however, might be evident also in relation to processes of visual attention such as orienting speed. It would be rewarding to investigate whether newborn high frequency cry can predict a slower attention orienting response in infants, since both attentional and crying processes share neural pathways related to alertness in central (e.g., limbic system and brainstem, reticular activation system) and peripheral nervous systems (e.g., vagal regulation) (Colombo, 2001; Lester, 2015; Sherwood, 2007).

Attention disengagement. Visual attention orienting occurs in three stages. First, attention is engaged to a target, disengaged from it, and finally shifted forward to a new target (Colombo, 2001). Initially in infant development, selective attention is more reflexive in nature but gradually infants learn to control their eye movements more voluntarily. With time this process of transitions begin to function seamlessly and after 2-4 months infants eventually gain the ability to more readily and easily disengage their attention from one stimulus to another (Colombo, 2001; Hunnius, Geuze, Zweens, & Bos, 2008; Johnson, Posner, Rothbart, 1991). This ease in ability is more prominent in older infants (Colombo, 2001). Infants who disengage easily (i.e., showing frequent shifts of attention between different objects and stimuli) are generally thought to show the most efficient and broadly distributed attentive capabilities thus improving overall information processing (e.g. Jankowski, Rose, & Feldman, 2001). Attention disengagement ability is believed to reflect the maturational state of the brain and to be one of the best candidates for separating infants with differing information processing abilities (e.g. Hunnius & Geuze, 2004).

The use of facial expressions as stimuli of which to disengage from provides an advantage in studying attention disengagement. Infants are known to find looking at faces rewarding and motivating. Infants' attentiveness and interest to a growing variety of facial expressions increases critically at 5-7 months (Leppänen & Nelson, 2009). Especially fearful faces provide important cues in infants' lives after 6 months and generally 7-month-old infants in general find it more difficult to shift their attention away from a fearful face compared to 5-month olds (e.g., Peltola, Leppänen, Mäki, & Hietanen, 2009). Naturally, non-face stimuli, such as blurry images, are much easier stimuli to disengage from compared to different facial expressions (Leppänen et al., 2011). It has been found that fearful faces are the hardest to disengage from compared to happy faces and neutral faces (Leppänen & Nelson, 2009; Leppänen et al., 2011). Having different facial expressions which to disengage from causes tasks to vary in difficulty. Thus, this allows differentiating infants who are very skilled at disengaging and infants who have difficulty at disengaging and observing their environment broadly, efficiently and flexibly, and hence instead are focusing and fixating on local features and need more time to familiarize with them (Jankowski et al., 2001).

1.5 Research questions and hypotheses

Overall, the connection between infants' neurological status and newborn cry f_0 has been fairly well established (e.g., LaGasse et al., 2005). However, when it comes to the developmental outcomes, little is known about how variation in the newborn cry f_0 characteristics predicts later developmental and social cognitive outcomes. There is evidence that newborn cry f_0 and variability in the f_0 are associated with long-term outcomes in cognitive development among infants having certain birth risk factors (e.g. Huntington et al., 1990; Lester, 1987). While high-pitched and highly variable cry frequency characteristics may be indicative of neural organization also in full birth weight and full-term newborns (e.g. Zeskind, 2013), the cry f_0 characteristics as indicators of later information processing outcomes have remained unstudied. Due to the preliminary nature of prior risk-group studies, further investigations for the predictive value of both cry markers to infant cognition are required in normative populations.

The aim of the present study was to investigate if cry frequency attributes (average f_0 and the variability of the f_0) could be indicators for later attentive regulation (attention orienting speed, attention disengagement probability). The first hypothesis of this study was that the cry frequency variables would predict saccadic reaction times as a measure of attention orienting speed. More explicitly, as high and variable cry f_0 features have been noted as risk factors for cognitive development, this study hypothesizes that high f_0 values would be connected to on average slower saccadic reaction times (SRT) since they may represent overall slower processing speed and orientation reflex (Luna et al., 2008).

The second hypothesis was that high mean f_0 values and high variability f_0 would predict less likely attention disengagement from facial and non-facial stimuli (i.e., a negative relationship), since higher attention disengagement probability would represent broadly distributed and flexible information processing associated with more maturity and efficient capacity (e.g. Jankowski et al., 2001). Disengagement from various facial expressions (i.e., joyful, neutral, and fearful) may be considered a sensitive measure since the facial expression stimuli at this developmental stage, 8 months, are very captivating for infants (Leppänen, Forssman, Kaatiala, Yrttiaho, & Wass, 2014). At the same time, disengaging from blurry and insignificant non-facial stimuli is likely to be far easier.

2 METHODS

2.1 Participants

This study was a part of a larger study in which a total of 104 families were recruited from the Tampere University Hospital Maternity Unit, Neonatal Ward Unit, and Intensive Care Unit in the Spring and Summer of 2014. The participants attended the follow-up visit at approximately 8 - 8.5 months from their expected date of delivery (*n* = 73), and the families who withdrew from the study did not need to give a reason for not attending the follow-up. In this study, the exclusion criteria used for follow-up attendees were birth risk factors such as prematurity (less than 37 pregnancy weeks; *n* = 2), low birth weight (less than 2500 grams; *n* = 3), and perinatal asphyxia (*n* = 2), which all may pose independent risks for developmental delays (Bear, 2004). Of the full-term, full birth-weight infants with no apparent neurological conditions who attended the follow-up visit (*n* = 66), 4 infants were too distressed to participate at the 8 month follow-up visit and thus the eye-tracking data could not be gathered. Furthermore, the eye-tracking procedure for 5 infants could not be performed due to the eye-tracking camera failing to detect the eyes of the participants in both tasks or otherwise due to technical malfunction. Eventually the sample consisted of 57 healthy infants with an adequate cry sample and successful trials in one or more eye-tracking paradigms (SRT task or Attention disengagement task).

Of these infants (*n* = 57), 33 were male and 24 female. They were born on the 37 - 41st pregnancy week. Apgar scores were all within the normal range of 7 to 10 (*M* = 8.96, *SD* = 0.42). At the time of the follow-up, the infants were on average 36 weeks old (*SD* = 1.0 week) in corrected age (i.e. days calculated from expected time of birth). Background information and health data were gathered from the medical records of Tampere University Hospital with the parent's written consent. The study was approved by the Ethics Committee of the Pirkanmaa Hospital District.

2.2 Cry recording and acoustic analysis of newborn cry

The cry recordings were conducted for the most part in the hospital or the patient hotel within 9 days from birth (*M* = 2.39 days, *SD* = 1.49 days). The cry emissions were recorded from a distance of 30 cm from the newborns' mouths. A Rode M3 -microphone stood on a secure stand as newborns lay on either the parent's lap, bed or on a care table. The digital recorder used in the recordings was a Tascam DR-100mkll linear PCM. Whenever possible, the cry was recorded as the first vocalisation began. Soothing and regular care procedures were generally not prohibited during the recording but the caregiver was instructed to avoid talking. Most cries followed diaper changing (47%), some followed non-invasive medical operations (e.g., measuring weight, 14%), and cries were also elicited by invasive medical operations (e.g., taking blood, 23%) which possibly may cause pain or increased distress to the newborn. The cry situation of some of the infants was undocumented (12%), and for a few the cause of crying was also relatively unknown and possibly hunger related (4%). As these cry conditions may have been associated with varying states of distress, the conditions were compared with independent-samples Kruskal-Wallis test. The undocumented (12%) and otherwise unknown cry cause (4%) situations were joined as one group for the analysis. No statistical differences were evident between the cry situations neither regarding the variability of the f_0 (i.e. mean $SD\ f_0$) ($H(3) = 2.717$, $p = .437$) or average cry f_0 (i.e grand mean (GM) f_0) values ($H(3) = 3.019$, $p = .389$).

The cry utterances were then analysed in two stages at the Department of Signal Processing at the Tampere University of Technology. In the first stage, the relevant cry portions were extracted from the raw signal and this process excluded background noise from the cry emissions. A researcher independently listened to the recordings to determine what was considered crying and what was considered fussing, and he was blinded to the medical and developmental history of the infants crying. The digital analysis tool was given manual annotations put to the program as examples of inspiratory (i.e. breathing in) and expiratory (i.e. breathing out) portions of cry (Naithani et al., under review). After the annotations, the software was trained to automatically identify and label the inspiratory and expiratory cry portions. This process differentiated the inspiratory and expiratory cry portions with a 25 ms frame-based accuracy of 89%. Only the expiratory portions of cries were used in the subsequent acoustic analysis, as these portions are most often identifiable as crying (see also Fuamenya, Robb, & Wermke, 2015). Cries with a duration less than 500 ms were excluded from this study’s analysis, as short cries are traditionally either excluded or analysed separately in cry studies (Fuamenya et al., 2015; Reggiannini, Sheinkopf, Silverman, Li, & Lester, 2013). Similar to prior cry studies, the cry portions used in the statistical analyses were the first 5 valid expiratory cries in the beginning of each infants’ cry recording (Michelsson et al., 2007; Rothgänger, 2003). One participant with only 3 cry expirations and two participants with 4 cry expirations were, however, included in the final sample. If over 60% of the cry segment was too noisy (see description, Fuamenya et al., 2015) for f_0 data retrieval and thus would have influenced the reliability of the data, that cry expiration was excluded and the next cry expiration was used instead. The variability value of the f_0 was calculated with the mean of the standard deviations in the cry f_0 across these first cries, by first calculating the f_0 values in each 25 ms frame and then counting the mean across the expiratory cries. Since the standard deviation is easily influenced by extreme values such as hyperphonation, it may be considered a sensitive measure for especially highly variable f_0 as opposed to for example small tremor-like fluctuation in the cry frequency (see e.g. Quick et al., 2009). The grand mean f_0 was calculated as the average of the mean f_0 across the first 5 cries.

2.3 Eye-tracking procedure at 8 months

Visual attention processes (disengagement probability and saccadic reaction time) were measured by eye-tracking, which is a valid and reliable method for studying visual information processing in infants (see Gredebäck, Johnson, & von Hofsten, 2010, for review).

Testing procedure. The child was positioned sitting in front of a 50 x 29cm monitor on the lap of the caregiver, at the optimal distance of 60 cm from the eye-tracking cameras mounted below to the monitor (Tobii TX300; Tobii Technology, Stockholm, Sweden). The height of the monitor was adjusted at eye-level. Because the eye-tracking cameras automatically recorded the eye movements, the caregivers were instructed to turn their head away from the screen and close their eyes during the measurement to exclude any possibility of interference (Gredebäck et al., 2010; Karatekin, 2008). The lights in the testing area were dimmed for the duration of the measurement, and the wall in which the monitor lay was cloaked by black curtains to further minimize distracting elements in the room. Prior to beginning the tasks, a 5-point calibration was conducted at least once to ensure that the eye tracking algorithms were adequately tuned to the infant's gaze and eyes (Gredebäck et al., 2010). After the calibration process, the SRT and Attention disengagement paradigms were presented in four alternating blocks which began with the SRT-task (see Figure 1). A single block of the SRT task consisted of 16 trials and the Attention disengagement block was in turn comprised of 24 trials. Images of smiling children and joyful music were presented between blocks if the infant appeared fussy and/or anxious while testing.

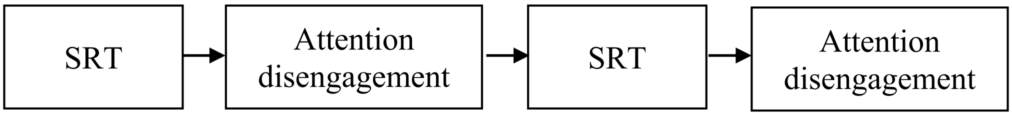


Figure 1. *Presentation order of alternating eye-tracking task blocks.*

In the saccadic reaction time (SRT) task (Figure 2A), each trial began with a gap period (i.e. blank screen) for 1000 milliseconds (ms). The checkerboard-like cue then appeared on the centre of the screen for 250 ms (see Leppänen et al., 2014) after which the cue rotated into its mirror image as a further means to attract attention, and remained stationary for at least 250 ms until the infant looked at it. When the infant looked at the central cue, the cue disappeared and the target appeared randomly in one of the four corners of the monitor (Figure 2B). However, the target did not appear more than 3 times in the same corner in a row. The target remained stationary in one of the corners until it was met by the infant's gaze. Saccadic reaction time was recorded as the time it took for the gaze to leave the centre of the screen and engage to the target appearing in one of the corners. Trials with SRTs longer than 1000 ms were excluded as a common procedure, in order to eliminate the trials during which the infant was looking away from the monitor or became distracted. After the infant's gaze met the target, the target remained visible in the corner for 750 ms. Then the target was replaced by an attractive stimulus, such as a toy or a cartoon animal, in the same corner location. Simple audio stimuli was also used as a means to attract attention to the task during cues and a specific sound followed also the infant's visual response to the correct corner location in the SRT task.

SRT task

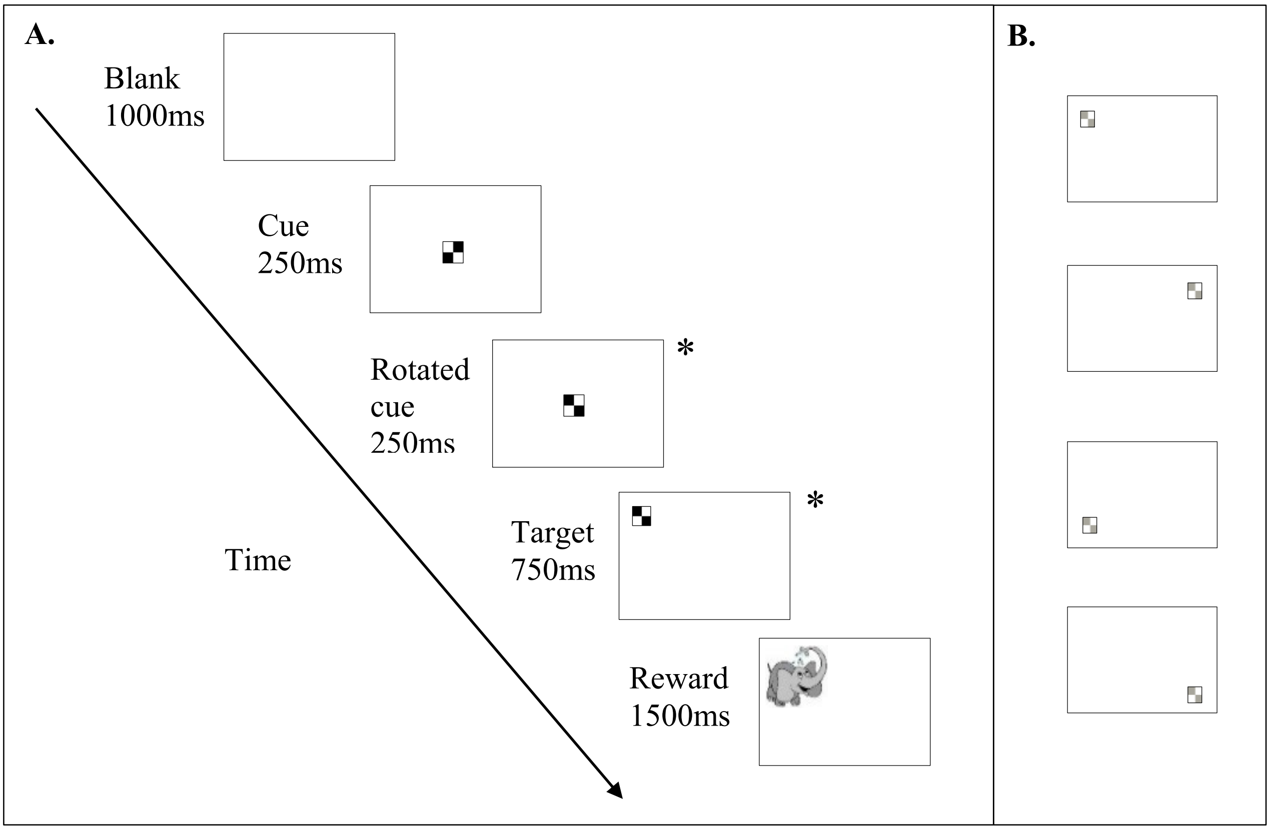


Figure 2. *Graphic representation of the SRT task presentation (A) and all possible target locations (B).*
Note: The SRT task had gaze-contingent parts in trial presentation that are marked in this representation by an asterisk symbol (*). Gaze-contingency means that stimulus presentation did not advance if the child was looking somewhere other than the area-of-interest at that time.

The Attention disengagement task. In the attention disengagement task, the facial stimuli of two female models and non-facial images (phase-scrambled rectangles) were used as central stimuli (see Figure 3B). The same female model appeared throughout the first block of the attention disengagement task, and the other model throughout the second block (see Figure 1). The trials began with the initial fixation period of 500 ms, after which one of the three facial expressions (happy, neutral, fearful) or the non-face control stimulus was presented alone for 1000 ms (Figure 3A). The facial expression stimuli and the control stimuli were presented in a random order, with the limitation that the same facial expression was not presented more than 3 times consecutively (see also Peltola et al., 2009). Following the facial or control stimulus presentation, a distractor stimulus (checkerboard pattern) was displayed randomly on either the left or right side of the overlapping central stimulus. The distractor was not, however, presented more than 3 times consecutively on the same side. The distractor stimuli was stationary for 250 ms and then it flickered into a mirror image shown for another 250 ms. After the distractor stimuli had disappeared, the face remained for another 1000 ms before finally disappearing.

Attention disengagement task

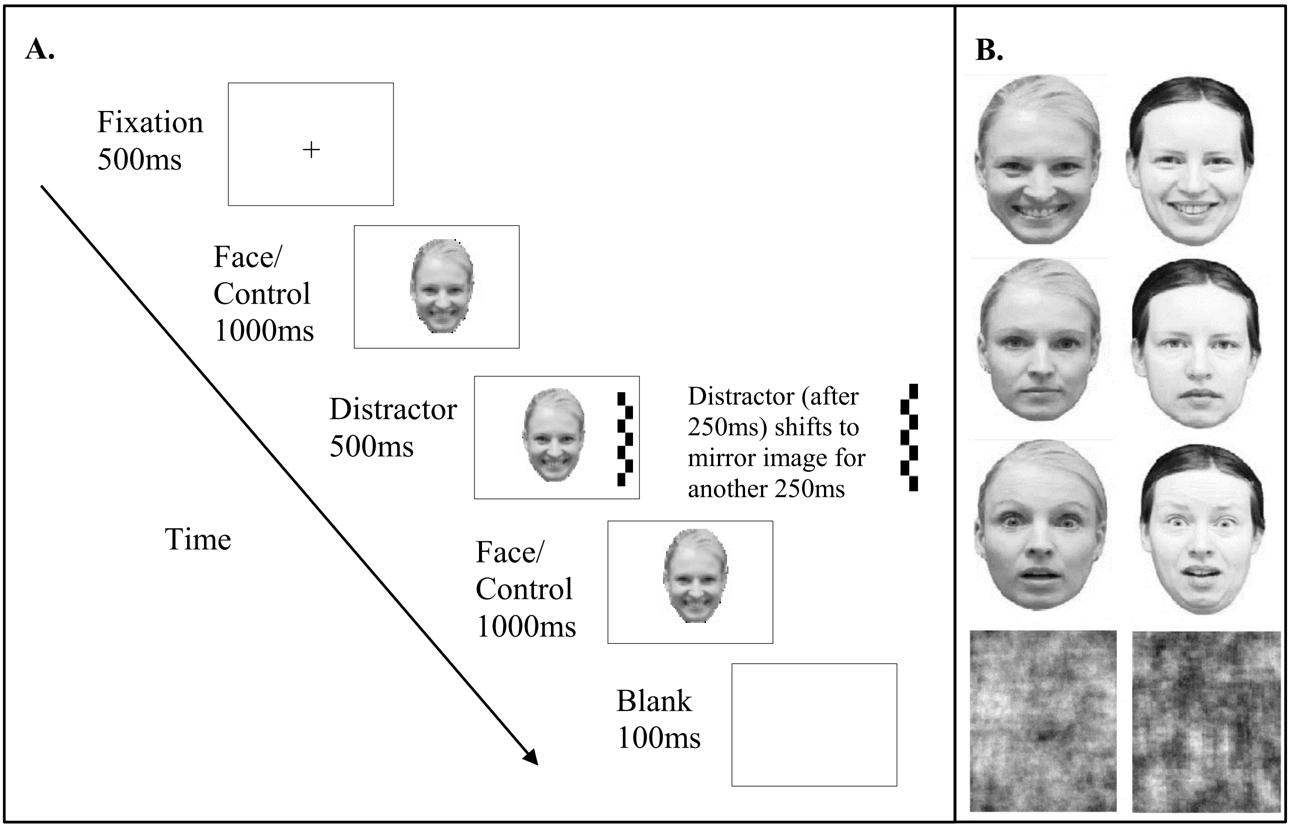


Figure 3. *Attention disengagement task presentation (A) and stimulus faces and non-face control stimuli (B).*

An attention shift toward the distractor was counted by a coding period; 150 ms after the distractor's appearance lasting for 1000 ms. If the eye movement shift did not happen within this time frame it was counted as "not disengaging". The probability of disengaging for each condition (i.e. neutral, joyful, fearful, non-face) was calculated as:

$$1 - \frac{\text{frequency of trials where no disengaging took place}}{\text{frequency of all successfully measured trials}}$$

These 0 to 1 values were multiplied by 100 so that the probability would be represented in percentages (0-100%). Thus, zero values would represent not disengaging at all from center stimuli and the maximum value 100 represented attention disengaging 100% of the time from the center stimuli. For criterion validation purposes, the mean probability of attention disengagement for each condition was tested in relation with the SRT task. The strongest negative correlation between with the SRT task and the disengagement probabilities occurred when all the probabilities were combined to a single mean disengagement index (see Table 2). The relation indicated expectedly that as the SRTs were longer, the probability of attention disengagement was smaller. Accordingly, shorter reaction times were related to disengaging with a higher probability. The index was calculated as the mean of all disengagement probability conditions, and as such, it included all the different central stimuli.

Table 2

Infant attention disengagement probabilities across trials: Bivariate correlations with SRT

Variables	1.	2.	3.	4.	5.	6.
1. Mean SRT	—					
2. Mean Disengagement probability, (mean of all situations)	$-.507^{***}$	—				
3. Disengagement probability, Non-face control situation	$-.449^{**}$	$.780^{***}$	—			
4. Disengagement probability, Neutral situation	$-.408^{**}$	$.787^{***}$	$.620^{***}$	—		
5. Disengagement probability, Happy situation	$-.436^{**}$	$.725^{***}$	.271	$.448^{**}$	—	
6. Disengagement probability, Fear situation	$-.409^{**}$	$.801^{***}$	$.431^{**}$	$.530^{***}$	$.580^{***}$	—

Spearman rho correlation (2-tailed), $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$, n ranging from 44 to 48 based on missing data.

2.4 Statistical analysis

Statistical analysis was performed with an SPSS version 22.0 (Statistical Package for Social Sciences, 2013), and the the alpha level for statistical significance was set at .05.

Split-half reliability analysis for odd and even trials was conducted to determine whether the data collected were reliable for SRT task. For the attention disengagement task data, split-half reliability analysis for odd and even trials was also conducted for the individual condition means prior to making the index variable with Spearman rho (r_s), as non-normally distributed probability variables could not be successfully transformed into normally distributed variables. Internal reliability analysis was conducted for the mean disengagement probability index (Pearson *r*, 2-tailed).

Initial graphic examinations and statistical analysis was done to examine the normality of the variable distributions. Based on this examination, normality was assumed for the SRT values and the mean probability of disengagement index, birth weight, birth head circumference and chronological age. The variability of the f_0 (Mean *SD* f_0) displayed slight tendencies for bimodal distribution, however, assumption for normality was adequately met (Shapiro-Wilk, $p > .05$). With the grand mean f_0, the tendencies for bimodal distribution were more prominent and additionally positive skewness accounted to a non-normal distribution (Shapiro-Wilk, $p = .007$). Log-transformation was adequately successful in normalizing the Grand Mean (*GM*) f_0 distribution (Shapiro-Wilk, $p > .05$). Pearson *r* (1-tailed) was used in testing bivariate and partial correlations between independent and dependent variables in order to test the research hypothesises regarding effect direction.

The child's gender, birth weight, birth length, birth head circumference and chronological age at the follow-up were considered as variables to be controlled in the correlation and regression analysis since these factors are well known to affect the neural development of the infant and thus might affect the cognitive outcome of the child. The chronological age of follow-up attendees also varied, since the corrected age, at which the scheduled follow-up was based on, accounted for the weeks of pregnancy the infant was born. The sample size limited the amount of predictors to 5, thus a maximum of 3 covariates were to be chosen for each model. The covariates were selected based on the following principle; the covariate correlated as much as possible with the outcome variables, yet, had small inter-correlations with other chosen covariates (see Appendix A for correlations). The chosen covariates were the same for both partial correlations and multiple regression models predicting SRT and the Disengagement probability: chronological age at follow-up, birth weight, and birth head circumference.

Two multiple linear regression models were entered hierarchically with two steps. In the first step only the covariates were fitted in the model explaining the outcome variables. In the second step, both cry variables were entered to the models. The change in R^2 between step 1 and step 2 was then examined and tested using an F_{Change} -ratio to determine whether the cry variables made a significant contribution to the model after chronological age at follow-up, birth weight, and head circumference contributed to the outcome variable had been taken into consideration.

Assumptions for regression analyses. Regarding both of the two multiple regression models (and the 2 blocks within both two multiple regression models), analyses of standard residuals and standardized scores indicated that none of the variables had significant univariate outliers (min z-score = -2.65, max z-score = 2.33) or multivariate outliers (max Cook's $D = 0.23$). Hence, no values were removed. Data met the assumption of collinearity. The assumption of independent errors was met, and all the errors had normal distributions when $GM\ f_0$ was log-transformed. The scatter plots of standardized residuals indicated that the assumptions of homoscedasticity and linearity were met for each regression model. The predictors entered into the regression model all had non-zero variances, indicating that the values were not identical.

3 RESULTS

3.1 Internal reliability of outcome measures

On average infants (n = 57) had 18.86 (SD = 9.886) successful trials on the saccadic reaction time (SRT) task. Split-half reliability for the SRT mean values between odd and even trials was relatively low, r = .63, p < .001, when using all the data available from all participants (n = 57). The SRT task showed a satisfactory split-half reliability of SRT mean values between odd and even trials (r = .77, p < .001) when it was measured from 3 or more trials. Reliability did not significantly improve by limiting the minimum number of successful trials to more than 4 or 5. Thus, participants (n = 54) with at least 3 successfully measured SRT trials, of which the average SRT value could be computed, were included in the analysis.

In the attention disengagement task, infants had on average 8.11 (SD = 3.409) successful trials in the non-face control condition, 8.94 (SD = 3.060) in the neutral condition, 8.72 (SD = 2.692) in the happy condition, and 9.15 (SD = 2.866) in the fearful condition. This constituted as 8.84 successful trials on average (SD = 2.574) across conditions. Split-half reliability scores for odd and even trials in each stimulus condition were computed with Spearman rho (r_s). Reliability scores were low when no limitation was made on the amount of successful trials (r_s ranging from 0.39 to 0.60) but improved when limiting the minimum of successful scored trials to two per facial expression task and non-face control task (n = 44) (Non-face control: r_s = .537, p < .001; Neutral: r_s = .413, p < .01; Happy: r_s = .726, p < .001; Fearful: r_s = .584, p < .001). This indicated that infants in general behaved most incoherently between different neutral trials and, in contrast, more consistently in the same way across happy trials. Increasing the minimum limit of successful trials to three per each facial expression task and control task did not increase reliability sufficiently (n = 43) (Non-face: r_s = .475, p = .003; Neutral: r_s = .342, p = .033; Happy: r_s = .726, p < .001; Fearful: r_s = .653, p < .001). Hence, an inclusion limit was set on two minimum trials per condition, and 44 infants met this criterion. Although infants' behaviour in individual conditions was varied, Cronbach's alpha (n = 44) for the combined mean disengagement probability (all conditions combined, min 2 successful trials for each condition) was .768, thus indicating that the index as a whole had satisfactory reliability.

3.2 Descriptive results

The birth weight of newborns ($n = 57$) was on average 3465.05 grams ($SD = 444.36$ grams (g)), ranging from 2660 g to 4700 g. Infants had no neurological findings deviating from normal. The birth head circumference was on average 34.82 centimetres ($SD = 1.37$ centimetres (cm)), varied from 31 cm to 38 cm. At the follow-up visit, infants' ages varied from 216 to 286 days ($M = 254.26$ days, $SD = 12.35$ days), on average being 36 weeks. Descriptive statistics on outcome variables and cry variables are displayed in Table 3.

Table 3

Descriptive statistics of outcome variables and cry predictor variables

	M	*SD*	*Min*	*Max*	*n*
Mean SRT (ms)	421.56	52.94	281.30	544.70	54
Mean disengagement probability (%)	35.43	19.09	2.27	82.5	44
Grand mean f_0 (Hz)	464.93	61.92	368.76	596.67	57
Log- Grand mean f_0	6.13	0.13	5.91	6.39	57
Mean $SD\,f_0$ (Hz)	65.72	26.39	17.13	123.03	57

3.3 Correlation results

Correlations were used to test the univariate effects between the predictor and the outcome variables. Pearson's correlation supported the research hypothesis that as the newborn cry frequency average increased, the probability of attention disengagement decreased, as there was a significant negative correlation between log-$GM\,f_0$ and disengagement probability ($r(42) = -.31$, p (1-tailed) = .019). The variance that log-$GM\,f_0$ could account in disengagement probability was 9.9%. Variability of the cry f_0 (mean $SD\,f_0$) and attention disengagement probability were not significantly related ($r(42) = .019$, p (1-tailed) = .451). Table 4 illustrates partial correlations between the independent and dependent variables in comparison to the bivariate correlations. Noteworthy to interpreting partial correlations, there was strong significant correlation between the cry variables (log $GM\,f_0$ and $SD\,f_0$) ($r(55) = .512$, $p < .001$). As the average cry f_0 was higher, the cry f_0 quality was also on average more variable and unstable. Other intercorrelations of predictors are displayed in Appendix B. It can be observed from Table 4, that the relationship between mean cry frequency (log-*GM* f_0) and mean disengagement probability remains significant when the influence of infant body size measures (birth weight, birth head circumference), age, and cry variability have been held constant. Body size measures were uncorrelated to cry f_0 variables (Appendix B). Overall, these partial correlation results indicate that log Grand mean f_0 was the strongest of all of the examined predictors when the information the other predictors contributed had been taken into consideration. Thus, it could account to unique variance in attention disengagement probability.

Higher average cry frequency was not related to saccadic reaction times, as there was no significant correlation between log-*GM* f_0 and mean SRT ($r(52) = .045$, p (1-tailed) = .373). The variability of cry frequency was also not related to saccadic reaction times, since mean *SD* f_0 did not correlate with mean SRT ($r(52) = -.11$, p (1-tailed) = .215). It can be observed from Table 4 that the effects of the cry variables on the SRT remain non-significant once the other predictors have been controlled for. Overall, based on these bivariate and partial correlation results, the cry variables do not serve as predictive markers for saccadic reaction times.

Table 4

Bivariate correlations and partial correlations of each predictor to the outcome variables

	Outcomes			
	Mean SRT (ms), $n = 54$		Mean disengagement probability (%), $n = 44$	
Predictors	Bivariate correlation	Partial correlation	Bivariate correlation	Partial correlation
Chronological age at follow-up	-.25*	-.21	.18	.01
Birth weight	.09	-.09	-.40**	-.21*
Birth head circumference	.20	.15	-.29*	-.12
Log- Grand mean f_0	.05	.14	-.31*	-.31*
Mean SD f_0	-.11	-.15	.06	.15

Pearson r (1-tailed), $^*p < .05$, $^{**}p < .01$

Note: In partial correlation the effects of other predictors listed in the table have been controlled for and held constant.

3.4 Multiple regression models

Saccadic reaction times. Multiple regression analysis was used to examine whether the newborn cry variables (Grand mean f_0 and mean SD f_0) predicted saccadic reaction times when the effects of infants' age at 8-month follow-up, birth weight and birth head circumference to SRT were taken into account. Both the first step of the hierarchical model (newborn body measures and age at follow-up) and the second step (newborn body measures, age and cry variables) were poor fits to the data. At the first step, the model did not predict saccadic reaction times better than the mean value of SRTs ($F(3, 50) = 1.524$, $p = .220$, $R^2 = .084$, $R^2_{Adjusted} = .029$), and the model accounted only 8.4% of the total variance in reaction times. The individual *b*-values for both the first step were all non-significant (see Table 5).

Table 5

Multiple linear regression model predicting mean SRT (ms), (n = 54)

	b-values, (Standard error)	
	Step 1	Step 2
Intercept	467.239 (283.362)	105.865 (520.522)
Birth weight (grams)	-0.010 (0.019)	-0.012 (0.020)
Birth head circumference (cm)	6.669 (6.123)	6.786 (6.437)
Chronological age at follow-up (days)	-0.962 (0.632)	-0.972 (0.639)
Log Grand mean f_0 (Hz)		63.409 (66.020)
Mean SD f_0 (Hz)		-0.328 (0.322)

Notes: Variables were entered hierarchically in two steps. All individual unstandardized b-coefficients were non-significant, p > .05

After including the cry variables in the second step, the model was also not significant at predicting reaction times (F(5, *48*) = 1.167, $p = .339$, $R^2 = .108$, $R^2_{Adjusted} = .016$), and the full model explained 10.8% of total variance in reaction times. The second step -model gained very little predictive power by including the cry variables, as both cry variables accounted for 2.5% of the total variance in reaction times. Based on these results, the cry variables together do not appear to not make a significant contribution in the second step compared to the first step ($R^2_{Change} = .025$, $F_{Change}(2, 48) = 0.663$, $p = .52$). The individual *b*-values for the second step were also all non-significant (Table 5). This indicated, in a similar vein to the correlation results (Table 4), that none of the predictor variables was significantly related to reaction times.

Mean disengagement probability. A multiple linear regression model was also computed hierarchically in two blocks to predict disengagement probability. In the first step of the model, age, birth weight and birth head circumference were entered as predictors. The overall fit of the first step of the model was not an adequate fit and the regression equation was only marginally significant (F(*3, 40*) = 2.660, $p = .061$, $R^2 = .166$, $R^2_{Adjusted} = .104$), explaining 16.6% of the variance in attention disengagement. Birth weight was the only marginally significant contributor ($t(38) = -1.900$, $p = .065$) in the first step of the model (see Table 6 for individual *b*-coefficients), and all other coefficients were not significant. In the second step, the cry variables were included as predictors. At the second step, the model was a good fit to the data (F(*5, 38*) = 2.465, $p = .0498$, $R^2 = .245$, $R^2_{Adjusted} = .146$), and significantly explained disengagement probability by accounting for 24.5% of its variance. The intercept was the only significant contributor in the second step of the model ($t(38) = 2.103$, $p = .042$) with the log $GM f_0$ having a marginally significant contribution to the model ($t(38) = -1.981$, $p = .055$). These results indicated that as a whole, the predictors worked together to predict attention disengagement significantly, although none was directly related to attention disengagement on a level exceeding statistical significance.

The cry variables included in the second step of the model improved the fit of the model to be significant. The amount of change that both cry variables accounted for in the model was not statistically significant, however ($R^2_{Change} = .079$, $F_{Change}(2, 38) = 1.976$, $p = .153$). Thus, based on these results, the cry variables (mean $SD\ f_0$ and log-Grand mean f_0) together do not contribute a significant amount of information to the attention disengagement probability when the variance accounted by the covariates has been taken into consideration.

Table 6

Multiple linear regression models predicting mean disengagement probability, %, (n = 44)

	b-values, (Standard error)	
	Step 1	Step 2
Intercept	108.412 (113.645)	426.139 * (202.596)
Birth weight (grams)	-0.014 (0.007)	-0.010 (0.008)
Birth head circumference (cm)	-1.263 (2.468)	-1.988 (2.590)
Chronological age at follow-up (days)	0.075 (0.250)	0.016 (0.250)
Log Grand mean f_0 of cry (log, Hz)		-48.721 † (24.593)
Mean *SD* f_0 of cry (Hz)		0.110 (0.115)

*Notes: p-values of the t-tests for individual unstandardized b-coefficients, † p = .055, *p < .05*

4 DISCUSSION

This is the first study to look into the predictive value of cry frequency (f_0) characteristics in full-term full-birth weight newborns to their later information processing abilities. The aim of this study was to investigate if two cry frequency variables (perceived as the height and variability of the cry pitch) would be able to predict reaction times and attention disengagement measured at 8 months. The research hypothesis was constructed on the basis that higher frequency and more variable frequency overall in the cry could be considered as indicators of less mature patterns in regulating attention, as well as slower orienting and processing of information. Hence, the hypotheses stated that elevated and more variable cry frequency (separately and combined) would predict less likely attention disengagement and slower saccadic reaction times.

4.1 Main results

In this study, a long-term association emerged between newborn average cry frequency and visual attention disengagement probability at 8 months, and the negative direction of the relation was as hypothesized. Cry frequency as a newborn was negatively related to the average attention disengagement probability from different facial and non-facial stimuli. Hence, higher cry frequency would seem to be an indicator of less broadly distributed attention orienting. The effect size of the relation was moderate without considering other birth related factors and remained moderate when other predictors in this study were considered. It can be concluded from the partial correlation results and intercorrelation results that the relation between the average cry frequency and attention disengagement was not caused by birth-related factors (e.g. body size), but it is unclear whether it is completely independent of these factors. Since the partial correlation coefficient was not larger than the bivariate correlation, it is likely that the other predictors controlled for were not merely factors that explained the outcome but instead some may have contributed to a moderation effect. Hence, the predictive value of mean cry f_0 may be stronger with infants having certain attributes (e.g. certain body size, or variability in cry f_0). However, this is yet to be studied.

Against the research hypothesis, the variability in cry frequency was not significantly related to attention disengagement. Moreover, when the two cry frequency variables were combined with the information that newborn body measures (weight, head circumference) and follow-up age contributed, a regression model predicting attention disengagement yielded a successful equation that explained nearly a quarter (24.5 %) of the variance overall in attention disengagement probability at

8 months. Since the change of including both cry variables to the regression model was not significant, this indicates that the cry quality variables together do not have sufficient predictive power over attention disengagement on their own beyond the other predictors. The results imply that any practical application based solely on the two cry frequency variables is not justified. As also summarized in prior literature, cry f_0 is not a useful indicator of long-term development by itself and has to be used alongside other factors (Green et al., 2000). It can also be concluded from this study that the unique variance accounted by the mean cry f_0 could have the potential to detect less mature abilities of attention disengagement when used among other predictive factors. More research is, however, required to determine the strength of the predictive value of cry f_0 on attention disengagement, as in this study the results of the predictive power of mean cry f_0 were not fully congruent: while bivariate correlations and partial correlations indicate a moderate effect, the mean f_0 was not a significant contributor in multiple predictor linear regression. Although the results taken together support the conclusion that mean cry frequency indicates neural and autonomic nervous system organization in full-term infants regarding attention, further verification from longitudinal studies is required.

One hypothesis of the study was that the cry f_0 variables would be able to predict saccadic reaction times (SRTs) and that high and variable cry frequency would be related to longer SRTs. The results, however, were against the hypothesis that high and variable cry frequency in newborns are predictive markers for longer saccadic reaction times. Cry frequency variables provided no predictive power to SRTs and thus, based on this study, it seems that the speed of attention orienting is unaffected by newborn cry characteristics. It is important to note that while on the other hand the results indicate that there was a significant relation between newborn cry f_0 and visual attention disengagement probability, this would suggest that it is useful to explore the predictive value of cry to various information processing abilities in future studies.

Unlike prior studies (Huntington et al., 1990; Lester, 1987), this study found no relation between variability of f_0 (*SD*) and either of the cognitive outcome measures. Since there is little methodological consensus on how the variability of f_0 is determined, and only a few older studies report how the variable is constructed, this can make replication of prior cry studies difficult. The predictive qualities of other f_0 variability measurements should also be examined in future studies alongside standard deviation. Older studies have used, for example, interquartile range as a measure of variability, possibly due to its dismissing nature to extreme values (e.g. hyperphonation) and better suitability for non-normal distribution of a expiratory portion of f_0 values (Lester, 1995). Some more recent studies have also examined cry f_0 variability as an index variable of standard deviation that takes into account the average f_0 (Quick et al., 2009). However, in this study, the variability (*SD*) of f_0 was not significantly related to either of the outcome variables even when accounting for the average f_0 along with the other predictors. While this study addressed a more large-scale variability, measurements of small and tremor-like variability in cry frequency are more prominently being pursued in current cry research. One example of a sensitive micro-variation measure is f_0 fluctuation (Quick et al., 2009). It could be worthwhile to examine various types of subtle (e.g. fluctuation, interquartile range) and more coarse f_0 (e.g. *SD*, range) variability measures of newborn cries as predictors of later information processing abilities.

4.2 Crying and attention disengagement

According to prior research and theory, crying and attention are linked through central (e.g., limbic system, brainstem, and the reticular activation system) and autonomic nervous system (e.g., vagal regulation) organisation and function (Lester, 2015; Zeskind, 2013). According to theory (Lester & Boukydis, 1992), stress or immaturity may influence the structural integrity of neural organization in newborns. Furthermore, lack of integrity influences self-regulation, which may result in an imbalance of the autonomic nervous system: the sympathetic nervous system becomes dominant, while the parasympathetic nervous system functions less actively. When the inhibitory vagal input from the parasympathetic nervous system is lacking, this has fundamental effects on regulatory functions and cry f_0, which may then be reflected in attentional functions (Lester, 1976; 2015). Lester (1976) found that infants who cried with elevated cry frequencies were less likely to detect novel stimuli and respond to them with typical heart rate deceleration. In this study, the results were similar, yet, in a longitudinal setting: Newborn cry frequencies were negatively related to attention disengagement probability. Infants with high cry frequencies were on average less likely to disengage their attention from various faces and control image to a distracting peripheral stimulus. In this sense, infants were less likely to respond to a change by shifting attention toward a sudden stimuli. Based on these results, cry f_0 seems to indicate the later tendencies in distributing attention and selecting sensory information.

When regulation of arousal is altered, the infant is in a higher risk for less than ideal development in many regards (Zeskind, 2013). High newborn cry f_0 and highly variable f_0 are associated with low self-regulation, high negative affectivity in temperament (irritability) as well as attentional deficits (Lester, 1976; 2015). There is some evidence that in addition to self-regulation and executive function (Cuevas & Bell, 2014), also temperament and negative affectivity are intertwined with attention-related processes (e.g., Johnson, 1991; Nakagawa & Sukigara, 2012). Less disengaging from attractive central stimuli and fearful faces has often been related to temperamental tendencies such as low emotion regulation (Leppänen et al., 2011), although some studies have found no such relation (e.g. Forssman et al., 2014). It is possible that later on in life this autonomic imbalance caused by lack of integrity may be the starting point of sensitivity to processing negative information (e.g. trait anxiety), being more easily stuck in distressing states of emotion, and being biased not to shift attention away from negative facial stimuli. In order to identify infants most likely to develop biased information processing, further research on the predictive value of neurotypical infants' cry acoustics is needed.

4.3 Possible future directions in cry research

A worthy pursuit for further research would be to combine parental cry perception studies and objectively measured cry characteristics in predicting infant cognitive outcomes and information processing abilities. As cry is a graded signal that intensifies with potential danger to survival, one aspect of increased cry intensity is higher pitch. Higher and more variably pitched cries, even in the normative range, are interpreted as more urgent, aversive and annoying in order to ensure a fast and adequate caregiving response (Zeskind, 2013; LaGasse et al., 2005). Parental depression, however, may negate this typically occurring sense of urgency in high-pitched cries to being perceived as non-urgent, and studies suggest that high-pitched cries may even be perceived as the least urgent of all cries (Zeskind, 2013). This phenomena of "reverse synchrony of arousal" may reduce the amount of time which the parent feels necessary to synchronize arousal with infant (calming them) and on the other hand increase time it takes for the parent to respond to the cry (Zeskind, 2013). Cries with f_0 even in the normative range can create this reverse synchrony of arousal in depressed mothers (Zeskind, 2013). Hence, the intensity of infant cry can influence parental interactions that in turn can either foster or hinder cognitive development. Therefore, there is a need for future research to include parental sensitivity as a moderating factor when studying the relation between newborn cry and social cognitive outcomes.

There are other similar findings on moderation effects of parental sensitivity between cry and cognitive development. Lester (1995) adapted the goodness-of-fit model in his study on infant cry acoustics, and found that the caregiver's sensitivity to detect cry qualities that match those objectively measured in their own infant's spontaneous cry at 1 month of age predicted the child's later cognitive development at 18 months in preterm and full-term infants. The more the caregivers' estimates were in accordance with the parameters derived from acoustic analysis, the better the infant's cognitive outcome was on the Bayley Scales of Infant Development (MDI). Hence, according to a biosocial model, newborn cry can predict the developmental outcome both directly through its relation to the central nervous system and indirectly by affecting parenting (Lester & Boukydis, 1992). When parents interpret their newborns' cry signals correctly, this can lead to better developmental outcomes in infants whose cry is high-pitched (Lester, 1995). This speaks to the repairing influence that sensitive early life relationships may have on brain integrity (Siegel, 2012). In this study, during the 8-month follow-up period, parental sensitivity would have likely had some influence on infants' information processing abilities and brain development.

Neurophysiological sensitivity and lack of integrity in the central nervous system may be a cause of strain and misunderstanding in the parent-infant relationship when the infant cries, as parents are more likely to express negative affect towards their infants, when their own infant's cries are high-pitched (LaGasse et al., 2005). It is essential to study the various information processing abilities and investigate further if cry f_0 could be an indicator of later cognitive abilities, executive function and emotion regulation. Understanding the neurophysiological causes of both high cry pitch and possible regulation-related issues might encourage health care professionals and parents themselves to seek social support early on to provide scaffolding to child development. When caregivers understand why infants cry with an aversive high pitch, this might also help to form the bond between the parent and the infant, and reduce the risk of negative attitudes building up towards the child.

4.4 Strengths and limitations of the study

While this study suffered from certain caveats, it had many major strengths: This study was the first to explore relations between cry f_0 and information processing outcomes in a normative sample of infants. Moreover, the study utilized the reflexive cries of newborn infants and the outcomes were objectively measured with an established eye-tracking procedure. Since the sample was normative, there is no reason to assume that based on this study, cry f_0 is a risk marker for any clinically significant changes in information processing. However, this study provided some support to the notion that cry can directly indicate later information processing abilities even without noted birth risk factors. The results of this study provide verification to the neurophysiological connection of crying and attention, and encourage future studies to investigate this possible connection further.

A longitudinal setting was a major strength of this study. However, it also had the drawback of participant attrition. While the sample size in this study was much larger than in the previous two preliminary studies with infants with birth risk factors (Huntington et al., 1990; Lester, 1987), the sample size was too small for the results to be generalized to the normative population. The small sample size in this study is also an issue that influences the reliability of the results when considering the analyses conducted. For example, an over-specified model in multiple linear regression, with more predictors than optimal with respect to the sample size, can lead to less precise estimates. Thus, the study should be replicated with a larger sample. To help the data collection, automatic digital analysis on the extraction of cry f_0 values provides tools that enable larger size data collection in the natural and noisy hospital setting after birth (Naithani et al., under review). The sample should be even larger when eye-tracking is used. Since eye-tracking is a highly sensitive method, it also generally contributes to less successful trials than planned when participants are infants (Haith, 2004). One reason for this is that infants are quick to lose interest, become anxious at looking at the screen and move around. The challenge for future studies should be to strive to make the eye-tracking procedure as entertaining and relaxing as possible for both the infant and the caregiver, while at the same time attaining a rigorous experimental setting.

In this study, two important things need to be considered when interpreting the results of attention disengagement. Firstly, habituation to the distracting element (i.e., the peripheral stimulus) might influence the disengagement response by gradually lowering the probability of attentional shifts. Since the checkerboard distractor stimulus is the same across trials, infants may instinctively begin to pay little or no attention to it. At the same time, as efficient habituation may be considered a sign of quickly adapting and skillful information processing, this contradiction has to be taken into account when also considering higher disengagement probability to be indicative of more mature and flexible cognitive abilities. Varying the type of peripheral stimulus, for example using animations and faces as distractors, could motivate infants to pursue the distracting peripheral stimulus more than in this study and lessen the habituation.

Secondly, it is important to note that interest to faces and facial expressions is very relevant in socioemotional development and learning for infants. As an extreme example, if an infant would not realize the special importance of facial expressions and purely attend checkerboard-distractors every time, the lowered interest to faces might be considered somewhat atypical at 8 months (see also Peltola, Forssman, Puura, van IJzendoorn & Leppänen, 2015). Hence, a U-shaped relation between cry f_0 and attention disengagement probability could be evident in larger studies replicating this exact setting. In this case, higher mean cry f_0 might be a risk factor for the two extremes (not disengaging attention at all and disengaging attention all the time), since both extreme features might represent less than optimal information processing. In this study, log-transformation affected any curvilinear tendencies in the relation by making the shape of the relation more linear. Since interest to faces lowers the probability of attention shifts toward the distractor in the facial conditions, as a caveat, each participant's own interest to faces was not controlled in this study. Future studies could try to vary the central stimuli, and use faces and objects alike to control for the interest to faces.

The fact that the cries were recorded in their natural environments resulted in high ecological validity. One caveat for this approach was that the situations in which the cries occurred were not standardized. However, the cry frequency estimates did not vary between the cry situations, and the resulting cry estimates were within the same range as prior cry studies with normative newborn samples. This indicates that the characteristics of the cry f_0 were not significantly affected by a non-standardized recording situation. Automatic cry analysis tools have potential to be adaptive regarding cry situations (Naithani et al., under review), in addition to cry recording being an inexpensive and non-invasive method in gathering f_0 data. Therefore, it should be addressed if it is at all natural to divide cries into spontaneous cries, hunger cries, and pain cries, or whether some other taxonomy should be applied (Zeskind, 2013). For example, Rothgänger (2004) devised a taxonomy based on level of distress. In future studies, this could be used in accordance with other psychophysiological measurements (heart rate, skin conductance) to measure the amount of autonomic nervous system activation during crying.

4.5 Conclusions

Overall, the present study introduced many novel approaches and ideas and summarized theory from prior cry research. Since there are some limitations to interpreting the results, the findings should be considered preliminary. With further verification to the results, cry frequency could be used as one of many factors in a screening process for social cognitive support to the parent and infant, as the relation of cry frequency and attention disengagement rivals in terms of effect size some very commonly used developmental indicators: birth weight and birth head circumference. Further evidence of the relation between cry frequency and attention disengagement may eventually lead to engaging children with high frequency cry with more familial support and supportive day-care prior to rehabilitating interventions, if issues with attention regulation can be reliably predicted early on.

In summary, since research has been scarce in examining cry as a predictive marker of specific cognitive processes, this may be a useful direction to pursue in future studies. For example, higher and more variable newborn cry frequencies might be markers of risk for poorer and less mature information processing strategies that are reflected especially in the regulation of attention and other social cognitive functions in later infancy. This is one reason why more research should be conducted to examine the modulating effect of socioemotional risk factors at birth since these factors are well known to influence social cognitive development and attention processes. As the predictive value of cry f_0 may be stronger for infants in risk-groups for attention problems and executive function, it is also possible that full-term, full-birth-weight infants with certain additional attributes (certain birth weight, or high variability cry f_0) may also have more prominent predictive value from mean cry f_0 in this regard. Further research that verifies these results on the predictive qualities of cry f_0 may advance the knowledge on the neurophysiological basis of cry frequency, and eventually may have many implications to standardized screening of newborns in hospitals to employ early interventions.

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APPENDICES

Appendix A

Considered covariates

Table A1

Correlations with SRT and Mean disengagement probability and intercorrelations

	1.	2.	3.	4.	5.	6.	7.
1. Mean Disengagement probability	—						
2. Mean SRT	-.506***	—					
3. Chronological age at follow-up	.185	-.249	—				
4. Birth weight	-.415**	.087	-.367**	—			
5. Birth length	-.430**	.069	-.514***	.782***	—		
6. Birth head circumference	-.300*	.203	-.315*	.497***	.473***	—	
7. Gender	-.066	-.044	-.016	.058	.314*	.126	—

Pearson r, (2-tailed), **p* < .05. ***p* < .01. ****p* < .001.

Note: Sample size varied from 44 to 57 based on missing data.

Appendix B

Intercorrelations of predictor variables

Table B1

	Birth head circumference	Birth weight	Chronological age at follow-up	log *GM f*0	*SD f*0
Birth head circumference	—				
Birth weight	.497***	—			
Chronological age at follow-up	-.315*	-.367**	—		
log *GM f*0	-.179	.085	-.057	—	
*SD f*0	-.201	-.013	-.035	.512***	—

Pearson correlation (2-tailed) * $p < .05$, ** $p < .01$, *** $p < .001$, $n = 57$

Notes: Age at which follow-up was conducted was from estimated time of birth so impact of immaturity could be controlled for. Hence, chronological age varied more than gestational age at follow-up. Birth weight and head circumference are related to chronological age due to this connection.